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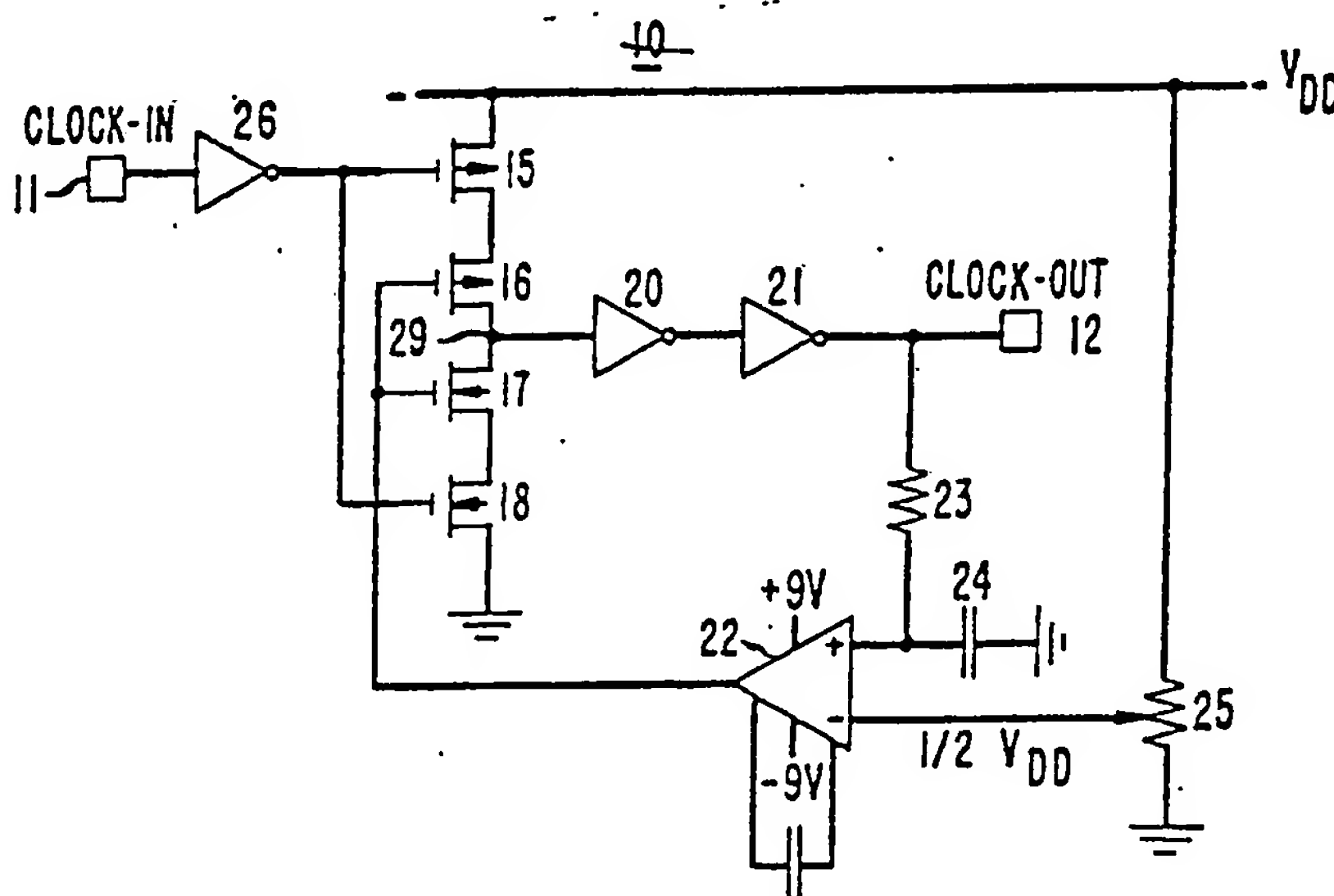
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(54) Title: CLOCK PULSE-SHAPING CIRCUIT



(57) Abstract

An op-amp feedback arrangement (Fig. 1, 23, 22, 29) is used to provide non-skewed clock pulses (at 12) from a source (11) of skewed clock pulses. Any skew in the clock-in pulses results in a change in the average voltage of a clock-out pulse at the output of the arrangement. The average voltage of the clock-out pulse is compared to a reference voltage (25) to produce a control signal which adjusts the average voltage at the output. Critical transitions in the clock pulses occur at precise time relationships under the control of the control signal.

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CLOCK PULSE-SHAPING CIRCUIT

Field of the Invention

This invention relates to a clock pulse shaping
5 circuit, particularly, to clock circuits for synchronizing
functional elements in semiconductor integrated circuits.

Background of the Invention

A microprocessor includes a datapath section as
well as logic and control sections. Each such section
10 includes functional elements which are clocked in order to
achieve synchronous operation.

One of the most difficult problems in the design
of a microprocessor is to generate skew-free clock signals
in order to synchronize the functional elements. The term
15 "skew" is defined as irregular variations in the timing of
transitions in the clock signal which occur primarily
because of the organization of the clock source itself.
For example, whenever a clock source includes a buffer, a
skew of the order of one nanosecond (1 ns) is inevitably
20 added. Also, when a clock source includes a counter, the
output waveform of the source is sensitive to layout
parasitics, process variations, temperature and the duty
cycle of the input clock. Consequently, skew in excess of
1 ns not only can occur but is difficult to avoid.

25 Brief Description of the Invention

The present invention is based on the recognition
that variations in the timing of transitions in a clock
signal are accompanied by variations in the average voltage
of that clock signal and that the voltage variations can be
30 made to adjust the timing of the transitions.
Specifically, a clock pulse-shaping circuit is achieved in
which a skewed clock-in signal at the input generates a
change in average voltage at the output. The change in
voltage is used to adjust a control voltage in a manner to
35 adjust the timing of the transitions.

Brief Description of the Drawings

FIG. 1 is a block diagram of a clock pulse-shaping circuit in accordance with this invention;

FIG. 2 is a graph of voltage versus time of a clock signal output from the circuit of FIG. 1;

FIGS. 3, 4, 5 and 6 are graphs of voltage versus time of actual clock signal outputs for different input clock signals of experimental duty cycles.

FIGS. 7, 8 and 9 are schematic diagrams of portions of a practical circuit arrangement in accordance with this invention;

FIG. 10 is a pulse diagram of the output of the circuit arrangement of FIG. 9; and

FIGS. 11, 12 and 13 are block diagrams of system organizations using the circuit arrangements of FIGS. 1 and 9.

Detailed Description

The invention is first described in general terms.

An input clock signal termed hereinafter a "clock-in" signal is supplied to the input of a clock pulse-shaper circuit including a series arrangement of inverters and a variable delay stage. It is assumed, for purposes of description, that the clock-out signal has a 50 percent duty cycle and that the clock-in signal has an undesirable duty cycle in excess of 50 percent leading to an average DC voltage of a clock-out signal of over $\frac{V_{DD}}{2}$. An op-amp, operative at a low speed to ensure that no clock frequency is transmitted, is used to compare the average output voltage to a reference voltage $\frac{V_{DD}}{2}$. The reference voltage is selected to provide a 50 percent duty cycle. As a consequence of the duty cycle being above 50 percent and the role of the low-speed op-amp, the pull-up time at the output is increased and the rising edge of the clock-out signal is delayed. A further consequence is that the clock-out signal approaches a 50 percent duty cycle clock pulse which is maintained if the op-amp has a high gain.

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Any skew in the occurrence of transitions in a clock-in signal appears as a much smaller skew in output transitions and a small change in the average voltage of the output. An op-amp is a well-known circuit element operative between V_{DD} and ground. If the positive input to an op-amp is slightly higher than the negative input, the output is $+V_{DD}$; if slightly less, the output is ground. In the transition region between V_{DD} and ground, the circuit has very high gain. The present invention employs such known op-amp negative feedback techniques to produce a novel clock pulse-shaping circuit.

More specific descriptions of the invention are now given.

FIG. 1 shows a clock pulse-shaping circuit including clock-in node 11 and output node 12 and adapted to suppress the effect of any skew in the clock-in signal at node 11.

The circuit comprises a series of two p conductivity type channel field effect transistors (FETs) 15 and 16 and two n conductivity type FETs 17 and 18 connected as shown between a source of voltage V_{DD} and ground. The drain electrodes of transistors 16 and 17 are connected to the clock-out node 12 by means of a series connection of two inverters, 20 and 21. The inverters 20 and 21 generate an output only when the the input voltage of node 29 exceeds a threshold voltage. The gate electrodes of transistors 16 and 17 are connected to the output of op-amp 22. The output voltage of op-amp 22 controls the conductivity of the transistors 16 and 17, hence the rate at which the node 29 can be driven towards a potential of V_{DD} when transistor 15 is turned on or towards a ground potential when transistor 18 is turned on. Each transistor pair 15,16 and 17,18 thus comprises a variable delay circuit, the extent of the delay (which determines when an output voltage is generated by the inverter pair 20 and 21) being a function of the output voltage from the op amp 22. Thus, for example, when the output of op amp 22 is

positive, the positive bias on the gate of p-channel transistor 16 decreases the conductivity of transistor 16, hence increases the delay provided by transistor pair 15,16. Conversely, the positive bias on n-channel transistor 17 increases its conductivity and decreases the delay provided by transistor pair 17,18. The positive input to op-amp 22 is connected to node 12 by a resistance 23 of typically 0.1 Megohm and is loaded typically by a 1000 picofarad capacitance 24. The negative input to op-amp 22 is connected to ground through a variable 5000 ohms resistance 25. The gate electrodes of transistors 15 and 18 are connected to the output of inverter 26, the input of which is connected to the clock-in input node 11.

15 In operation, the average voltage at node 12 is compared by op-amp 22 to a reference voltage for generating a control voltage to alter the timing of transitions in the clock-in signal. Specifically, an input clock pulse at node 11 is inverted by inverter 26 causing p-channel transistor 15 to switch on and n-channel transistor 18 to switch off. Let us assume, for convenience of explanation, that the output voltage of the op-amp 22 is $1/2 V_{DD}$. A reference voltage of $1/2 V_{DD}$ is maintained on the negative input of op-amp 22. A 50 percent duty cycle output is
20 ensured by adjusting the variable resistor 25.

A clock-in signal at node 11, of any duty cycle, is represented by solid curve 30 of FIG. 2. Curve 30 is assumed to have a duty cycle in excess of 50 percent. Consequently, the average DC voltage at node 12 is in excess of $1/2 V_{DD}$. Op-amp 22 and the resistor 23 and capacitor 24 are selected to have characteristics such that they do not transmit any clock frequency components but do transmit lower frequency signals. Since the positive input of op-amp 22 is higher than the negative input, the output
30 of the op-amp approaches V_{DD} . The result is that the pullup of transistor 15 towards V_{DD} is delayed and the pulldown of transistor 18 towards ground potential is
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accelerated by an amount proportional to the difference between the average DC voltage and $1/2 V_{DD}$ reference voltage. The clock-out signal is represented by broken curve 31 in FIG. 2. This results in a change in the duty cycle as represented by curve 31 appearing at 12 in FIG. 1. But the transitions occur such that times t_1 and t_2 satisfy $t_1 - t_2 = 1/2$ period.

To be exact:

$$(t_1 - t_2)_{out}^{-\frac{1}{2}} = \left[(t_1 - t_2)_{in}^{-\frac{1}{2}} \right] \div A$$

where A = gain of amplifier regardless of the delay (skew) in the clock-in signal.

An experimental circuit was built using RCA CD 4007 CMOS building blocks and a Western Electric 502T op-amp. FIGS. 3, 4, 5 and 6 are plots of voltage versus time at clock-out node 12 of FIG. 1 and were obtained by operating such a circuit. The figures show that in a range of duty cycles of the input clock (upper curve), from 10 percent to 80 percent, the output clock (lower curve) duty cycle is locked in at 50 percent.

FIG. 7 shows a circuit component utilized for generating an accurate pair of clock signals at a $1X$ clock frequency from the 50 percent duty cycle $1X$ clock generated by the scheme of FIG. 1. The clock-out signal is generated in a manner which permits independent control of the rising and trailing edges of the clock-in signal. FIG. 7 shows two sets of FETs 102, 103 and 104 and 105, 106 and 107, each set being connected electrically in series, as shown, between V_{DD} and ground. Transistors 102 and 105 are p-channel field effect transistors; the remaining are n-channel. The gate electrodes of transistors 102 and 103 are connected to an input node 110 and the drain-to-drain connection between transistors 102 and 103 is connected to the gate electrodes of transistors 105 and 106. The gate electrodes of transistors 104 and 107 are connected to a

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source of delay control signals C1 and C2, respectively. An output node 111 is connected to the drains of transistors 105 and 106. The circuit operates as a variable delay represented by block 120 in FIG. 8. Such a circuit is useful independently but is shown illustratively for use in generating non-skewed clock pulses as a part of a circuit described in connection with FIG. 9.

The circuit of FIG. 9 includes four NAND circuits 130, 131, 132 and 133. An input of each of NAND circuits 130 and 133 is connected to the output 111 by means of a series connection of inverters 134 and 135. Similarly, an input of each of NAND circuits 130 and 131 is connected to input node 110 via a series connection of inverters 137 and 138. An input to each of NAND circuits 132 and 133 is connected to node 110 via a series arrangement of three inverters 140, 141 and 142. NAND circuits 131 and 132 are connected to output node 111 via a series arrangement of inverters 150, 152 and 155. The circuit 120 of the type represented in FIG. 8 is connected between input node 110 and output node 111. A clock-out signal at output node 111 of circuit 120 is applied to the input of inverter 135 via a series arrangement of two inverters 160 and 161. The outputs of first and second op-amps 170 and 171 are connected to the C1 and C2 inputs to circuit 120. The outputs of NAND circuits 130 and 133 are connected to the negative inputs to op-amps 171 and 170, respectively, via associated inverters 180 and 181. Similarly, the outputs of NAND circuits 131 and 132 are connected to the positive inputs to op-amps 171 and 170, respectively, via associated inverters 182 and 183. The output of the associated inverters, in each instance, is connected via associated resistance and capacitances to ground.

The circuit of FIG. 9 is operative to generate a familiar four-phase clock-out signal as shown in FIG. 10 as follows: The series arrangement of two inverters, such as 137 and 138 or 134 and 135 or 160 and 161, does nothing but

delay an input pulse. The series arrangement of three inverters, such as 140, 141 and 142, or 150, 152 and 155, is designed to provide a delay equal to the associated arrangement of two inverters, e.g., 137 and 138, or 134 and 135, respectively. But the difference in number of series inverters (2 vs. 3) results in output pulses of opposite polarity. Thus, a clock-in pulse at 110 provides a delayed pulse on conductor 200 and an equally delayed pulse of opposite polarity on conductor 201. The result is a positive pulse applied to inputs to NAND circuits 130 and 131 and a negative pulse applied to inputs to NAND circuits 132 and 133. Similarly, clock-out signal waveform at output node 111 results in equally delayed positive and negative pulses applied to conductors 202 and 203 and thus inputs to NAND circuits 130 and 133 and to NAND circuits 131 and 132, respectively. The output signals from the NAND circuits are applied to inputs to the associated inverters and the requisite reference DC voltage levels are obtained via the associated resistance-capacitance arrangement to be applied to the inputs of the associated op-amps. The output signals from op-amps 170 and 171 are applied as control signals C1 and C2, respectively, to the gate electrodes of transistors 104 and 107 of FIG. 7.

Control signals C1 and C2 are voltage signals of values determined by the difference in the average (DC) voltage of the signal at the outputs of inverters 182 and 180 and inverters 183 and 181, respectively. Consider op-amp 170 which generates the C2 control signal. The input signals to op-amp 170 are from NAND circuits 132 and 133. The input signals to NAND circuit 132 are provided, one from the output of inverter 140 (from 110) and one from the output of inverter 150 (from 111). The input signals to NAND circuit 133 are from inverter 134 (from 111) and from inverter 140 (from 110).

A clock-in signal at 110 in FIG. 9 is operative to turn p-channel transistor 102 OFF and n-channel

transistor 103 ON (see FIG. 7). The delay time of the voltage signal on conductor 300 of FIG. 7 depends on the voltage level of control signal C1 which determines how fast transistor 104 turns on. The result is that the trailing edge of the voltage pulse on conductor 300 (and thus at node 111 of FIG. 9) is delayed an amount proportional to the voltage level of control signal C1. Similarly, the leading edge of a clock-out signal at output node 111 of FIG. 9 is determined by the voltage level of control signal C2 applied to (n-channel) transistor 107 (see FIG. 7). Thus, regardless of the amount of skew in the clock-in signal at 110 of FIG. 9, a non-skewed clock-out signal is generated at 111.

NAND circuits 130, 131, 132 and 133 may be replaced by NOR circuits and inverters 140 and 250 may be omitted.

FIGS. 11, 12 and 13 illustrate various circuit organizations of the clock pulse-shaping circuits of FIGS. 1, 7 and 9. The organizations are illustrated in terms of the circuit of FIG. 1. FIG. 11 illustrates a clock chip 400 with clock-in input 411 and clock-out output 412 corresponding to input 11 and output 12 of the circuit of FIG. 1. The non-skewed output is applied to functional elements of, e.g., a microprocessor chip via symbolic conductors 415 and 416. The functional elements are represented as blocks 417 and 418.

FIG. 12 illustrates an organization where a source of skewed clock pulses, represented as a block 500, applies pulses to a clock-in input 511 to, e.g., a central processing unit (CPU) block 512. The CPU chip includes the multistage delay arrangement of three inverters 526, 527 and 528 with a variable delay stage 529. These elements correspond to elements 26, 20, and 21 and the variable delay stage of FIG. 1, respectively. The op-amp is included in a separate "helper" chip 530. Chip 530 also includes a voltage averaging resistor and capacitor (not shown) corresponding to elements 23 and 24 of FIG. 1. The

clock-out output is identified at 532 and applied to inputs to chip 512 as well as to other chips. The control signal to the variable delay stage is applied to conductor 533.

FIG. 13 shows an organization where the entire clock pulse-shaping (circuit of FIG. 1 or FIG. 9) is included in a CPU chip 600. In such embodiments, an off-chip clock generator 601 applies pulses to a clock-shaping circuit represented by block 602 included within chip 600, non-skew pulses being generated at clock-out output 612. The clock-in input is represented by block 613.

It is important that the op-amp has a high gain characteristic. That is, an op-amp is chosen so that a transition from one voltage output level to another at the output of the op-amp occurs over a narrow input voltage range $V_+ - V_-$ in order to get an increasingly accurate feedback response.

It is also important that the output voltage levels from the op-amp vary over ranges more than V_{DD} minus the threshold voltage of the p-channel transistors and the threshold voltage of the n-channel transistors. In this manner, the variable delay stage has effective control over the signals.

Based on the understanding that skew produces change only in the average voltage of the clock-out signal at the output of inverter 161 in FIG. 9, it should be apparent that transitions in the clock-out signal at 161 can be set to occur at prescribed times by employing standard techniques such as a voltage divider circuit. Further, the invention has been described in terms of a reference voltage to provide a 50 percent duty cycle to achieve equally spaced clock edges (transitions). The reference voltage may be adjusted or set to provide a duty cycle different than 50 percent to permit the clock-out transitions to be located anywhere desired. It should be clear to one skilled in the art that a change in duty cycle can be made to produce a speed-up in chip performance.



CLAIMS

1. A clock pulse shaping circuit having an input (11) and an output (12) for generating at said output a clock-out signal having transitions which occur at first time separations and having an average voltage, said clock-out signal occurring in response to a clock-in signal applied to said input having transitions which occur at second time separations, characterized by variable delay means (15-18) connected between said input and said output, said delay means having a control input (transistor gate electrodes) for receiving a control signal for varying the delay in said stage in a manner to change said average voltage, and control means (22) responsive to changes in said average voltage for applying said control signal to said variable delay stage.

2. A circuit in accordance with claim 1 wherein said control means includes an op-amp (22) for comparing said average voltage to a reference voltage $1/2 V_{DD}$ for providing said control signal.

3. A circuit in accordance with claim 2 wherein said delay means comprises means (170, 171) for independently adjusting the timing of the leading and trailing edges of said clock-out signal.

4. A circuit in accordance with claim 2 wherein said op-amp is characterized by high gain.

5. A circuit in accordance with claim 1 wherein said control means has first and second control inputs (+,-) for providing said control signal of a value determined by the difference between first and second average voltages applied to said first and second inputs, respectively, said circuit also comprising means (V_{DD} , 25) for generating a first average reference voltage connected to said first control input, and means (23, 24) for generating a second average voltage connected between said clock-out output and said second control input, said circuit being operative to adjust the delay of

said clock pulses applied to said clock-in input as a function of the difference between said first and second average voltages.

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FIG. 1

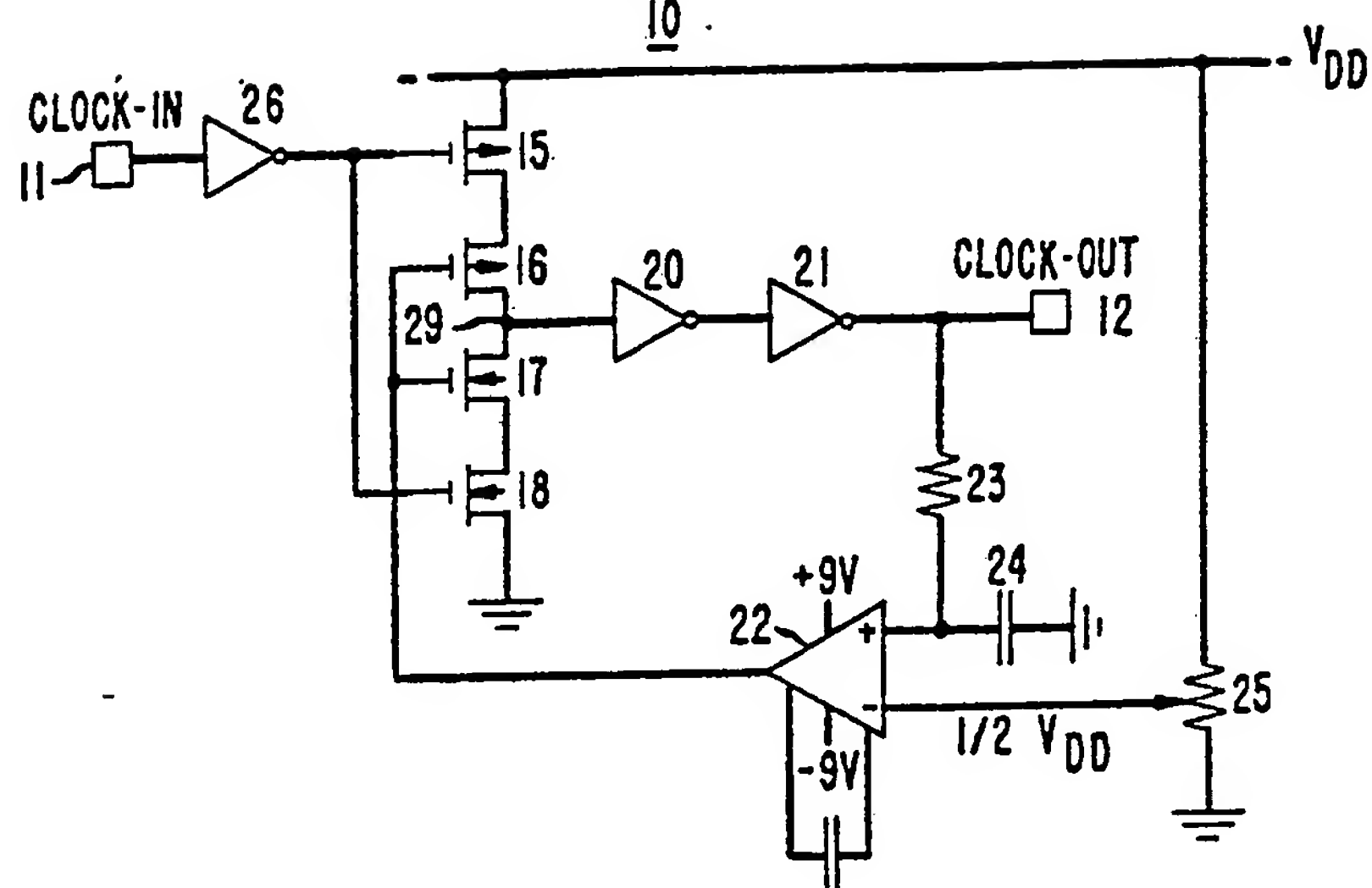


FIG. 2

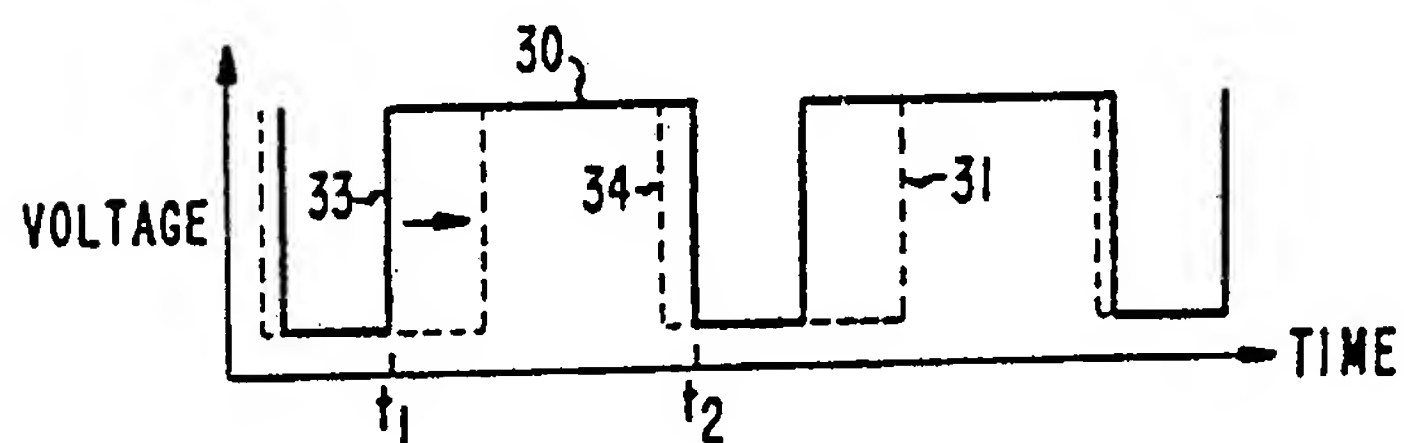


FIG. 7

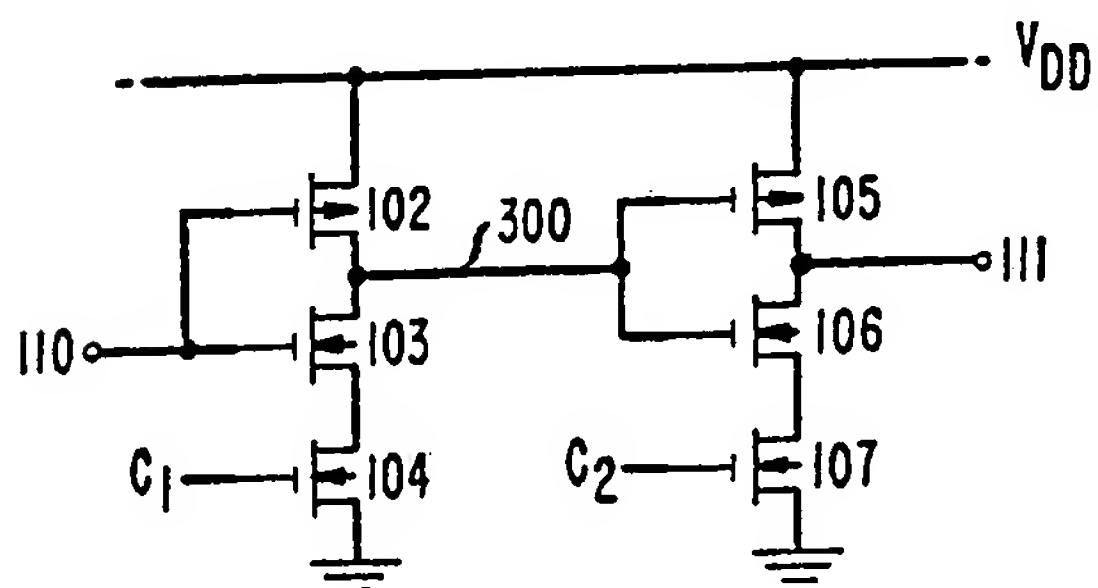


FIG. 8

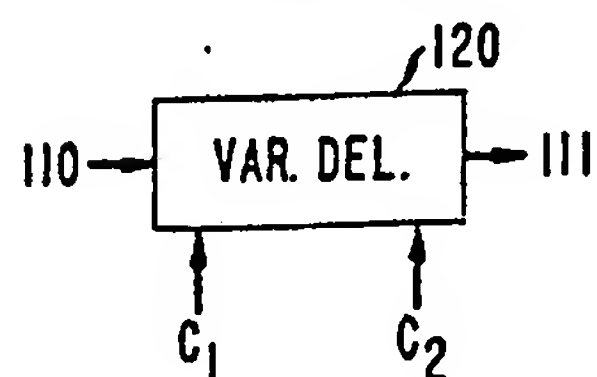


FIG. 5
DUTY CYCLE 60%

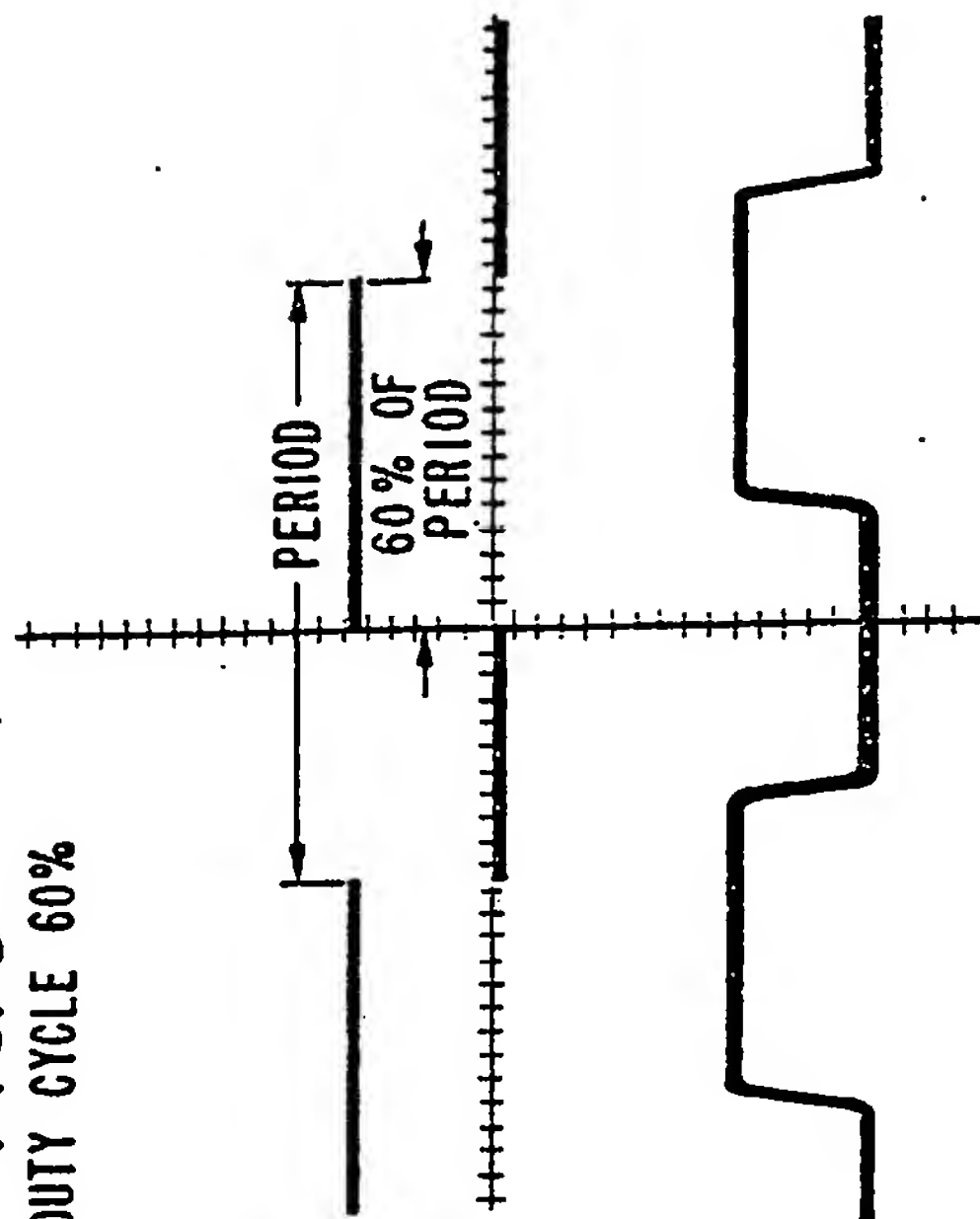


FIG. 6
DUTY CYCLE 80%

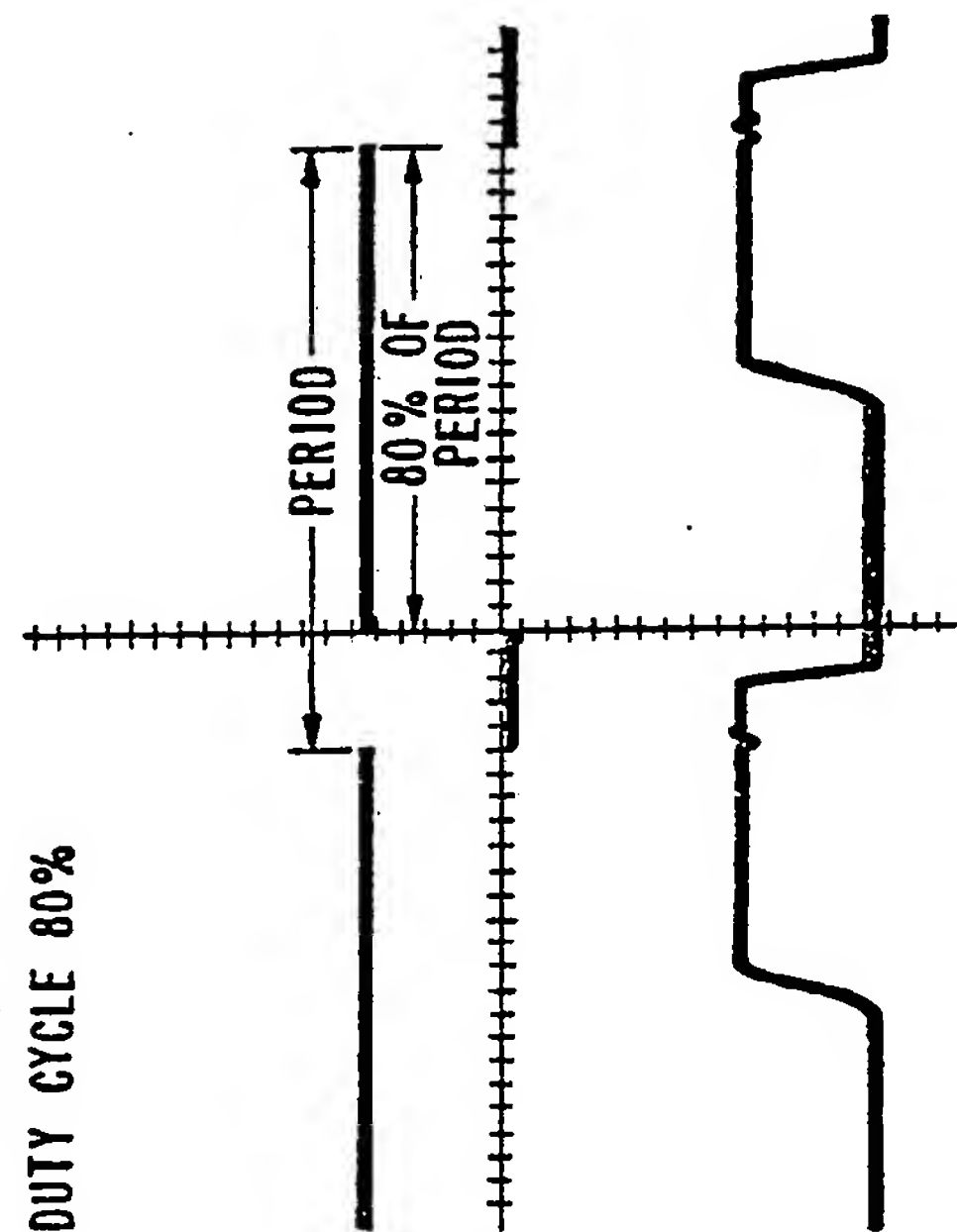


FIG. 3
DUTY CYCLE 10%

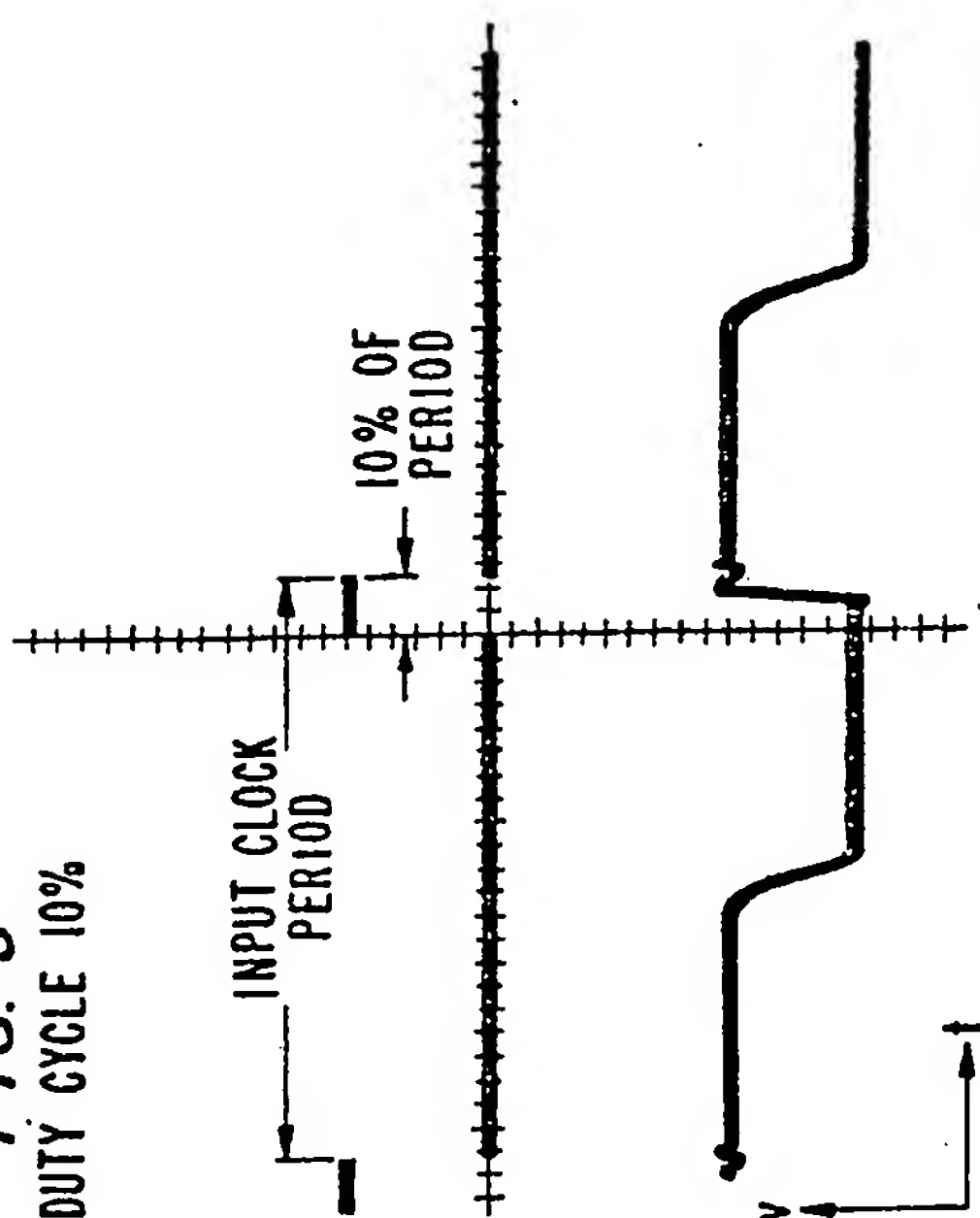
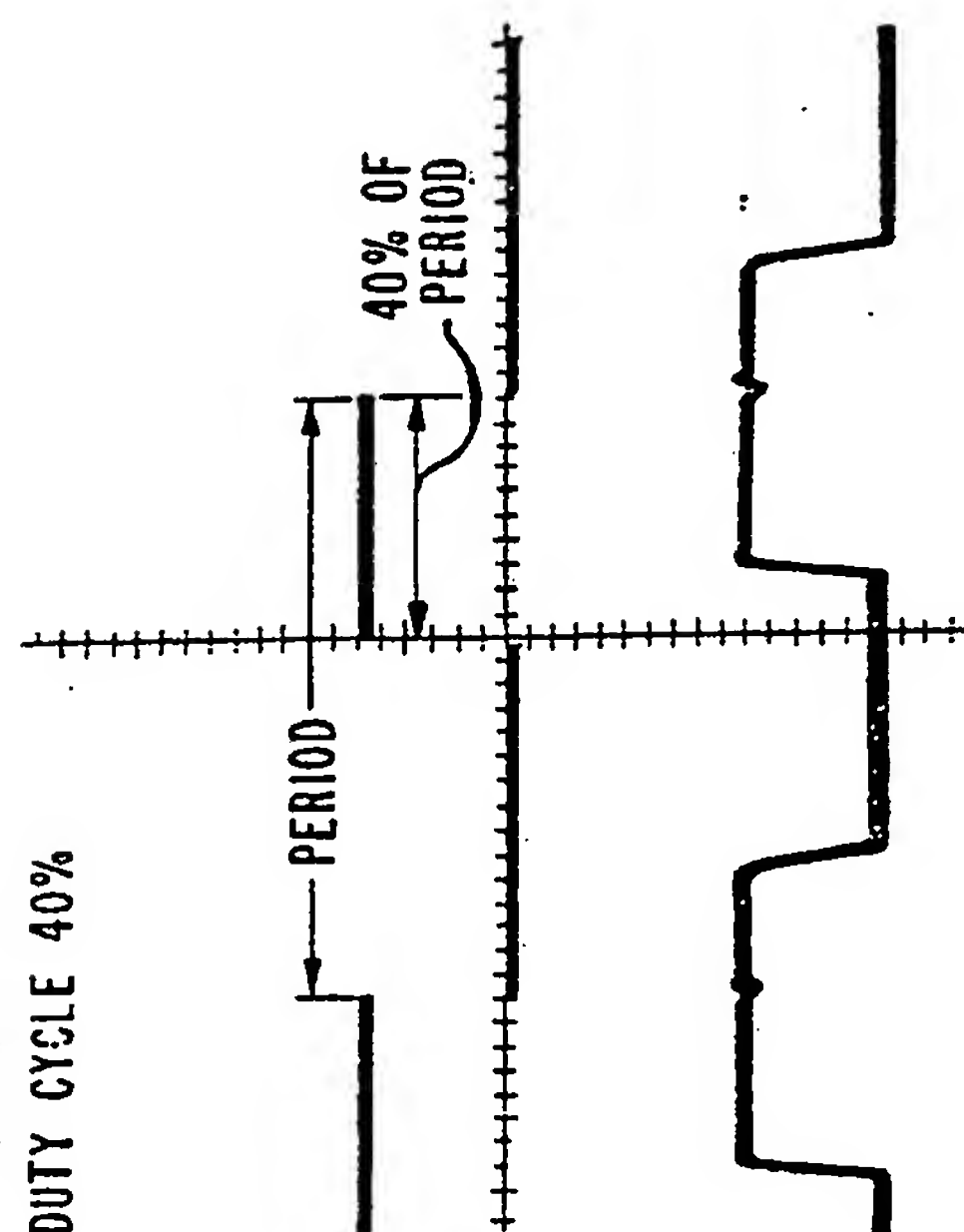


FIG. 4
DUTY CYCLE 40%



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FIG. 9

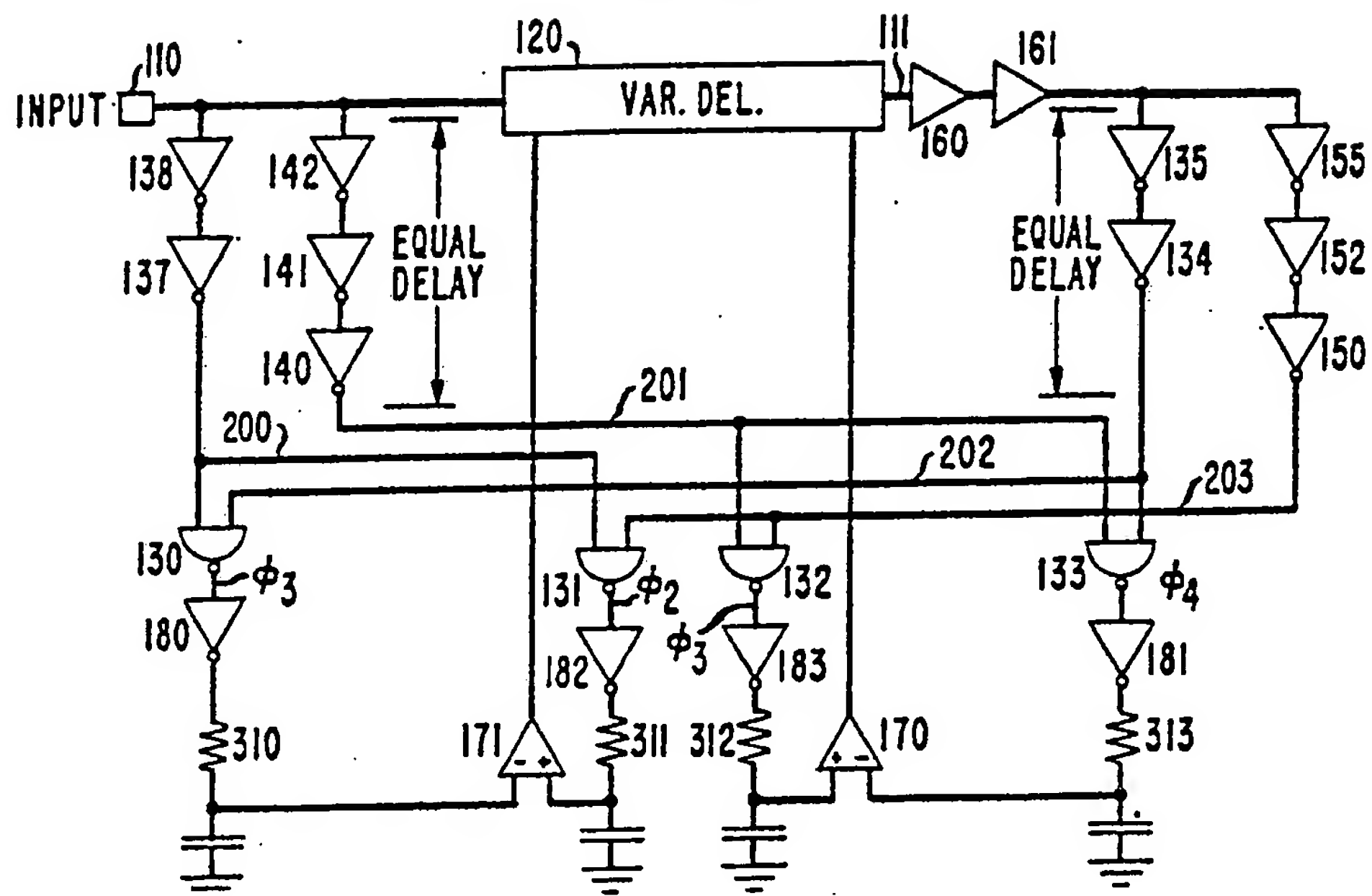


FIG. 10

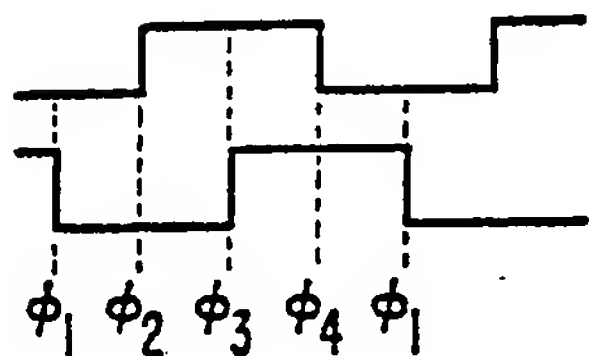


FIG. 11

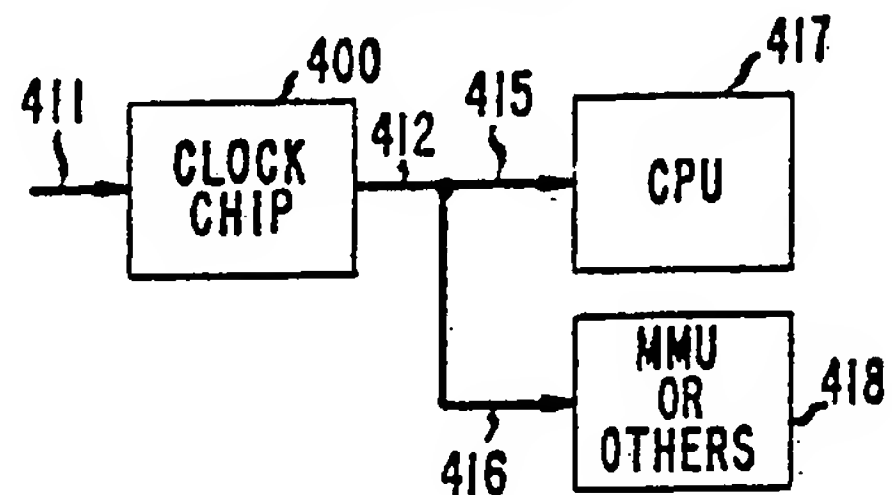


FIG. 12

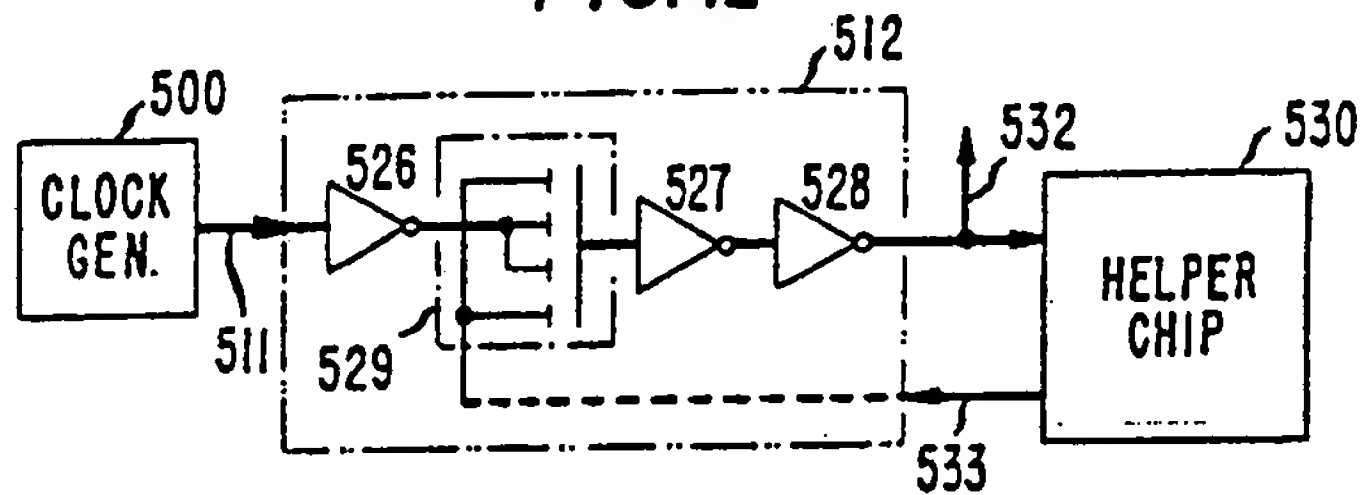
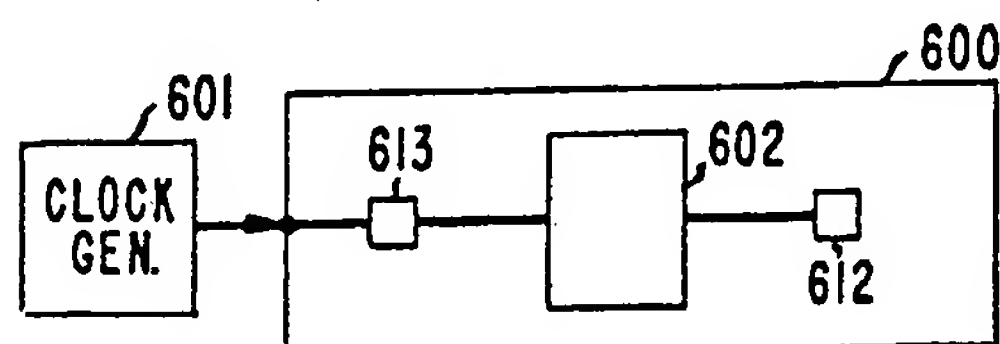


FIG. 13



INTERNATIONAL SEARCH REPORT

International Application No **PCT/US83/01897**

I. CLASSIFICATION OF SUBJECT MATTER (If several classification symbols apply, indicate all) ³		
According to International Patent Classification (IPC) or to both National Classification and IPC <div style="display: flex; justify-content: space-between;"> INT. CL. ³ H03K 5/04 </div> <div style="display: flex; justify-content: space-between;"> U.S. CL. 307/265; 269; 328/58; 371/61 </div>		
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III. DOCUMENTS CONSIDERED TO BE RELEVANT ¹⁴		
Category ⁶	Citation of Document, ¹⁶ with indication, where appropriate, of the relevant passages ¹⁷	Relevant to Claim No. ¹⁸
A	US,A, 3,712,994 (Graziani) 23 January 1973	1-8
A	US,A, 4,135,160 (Gagliani) 16 January 1979	1-8
A	US,A, 4,239,992 (Perkins) 16 December 1980	1-8
A	US,A, 4,241,418 (Stanley) 23 December 1980	1-8
X	US,A, 4,277,697 (Hall et al) 07 July 1981	1-8
A	US,A, 4,355,283 (Ott) 19 October 1982	1-8
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p>⁹ Special categories of cited documents: ¹⁵</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="width: 45%;"> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&" document member of the same patent family</p> </div> </div>		
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International Searching Authority ¹		Signature of Authorized Officer ¹⁰
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